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Cross-bedded sandstone of the Governors Point Member of the Chuckanut Formation at an outcrop west of Bellingham. S. Y. Johnson (USGS) interprets these as braided river deposits; their source was a rapidly eroding highland on and near Lummi Island. See related article, p.12. Photo by T. J. Walsh.

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Jenkins, O. P., 1924, Geological investigation of the coal fields of Skagit County, Washington: Washington Division of Geology Bulletin 29, 63 p.

Walsh, T. J.; Phillips, W. M. 1983, Rank of Eocene coals in western and central Washington State–A reflection of Cascade plutonism?: Washington Division of Geology and Earth Resources Open File Report 83-16, 21 p.

Petroleum Geochemistry of Washington—A Summary

William S. Lingley, Jr.
Washington Division of Geology
and Earth Resources
Olympia, WA 98504

and

Hans von der Dick
Canadian Hunter Exploration Ltd.
435 4th Avenue SW
Calgary, AB, Canada T2P 3A8

Although Washington is commonly thought of as an impoverished gas-prone province, some data do not support this view. These data include: (1) gas, condensate, and oil seeps and shows associated with Tertiary sedimentary sections throughout the state, (2) a dearth of wells drilled into petroleum-generative thermal environments, and (3) Type II kerogens in Tertiary sections of the continental margin and coal-bearing strata within the Puget trough that have gas- and liquids-generative potential.

Organic-rich shales and coals, which range from a few millimeters to about 15 m thick, are present in a variety of depositional settings, including turbidites of the western Olympic core complex (Snavely, 1987), graben-fill sequences of northeastern Washington (Gaylord, 1986), and tropical lower-floodplain deposits of eastern Puget trough. (See Beikman and others, 1961.) The area from which information for this article is taken is shown in Figure 1.

Figures 2 and 3 summarize some geochemical characteristics of these rocks as determined from analyses of 1,312 samples from 16 wells and seven measured sections (Brown and Ruth, 1984; Grady, 1985; U.S. Dept. of Energy, 1985; Sidle and Richers, 1985; Lingley and Walsh, 1986; Kvenvolden and others, 1989b; Palmer and Lingley, 1989; Bustin, 1990; Walsh and Lingley, 1991; this study). Measured organic carbon contents of these rocks are generally less than 1.5 percent, but enriched zones are present in most wells and measured sections. In general, Cenozoic nonmarine rocks of central Washington have better carbon preservation than coeval marine sections. S_2 pyrolysis values are generally less than 2.0, indicating fair kerogen preservation. (See Peters, 1986, for criteria.) Visual assessments and pseudo van Krevelen diagrams (Fig. 3) indicate that both marine and continental strata contain mainly Type III (gas-generative) and IV (inert) kerogens. However, rocks deposited along the Puget trough in continental environments have significant amounts of Type II (light-liquids- and gas-prone) kerogen (Fig. 3). The continental rocks appear to be hydrogen enriched relative to coeval marine and paralic rocks. Many of these kerogens have an amorphous appearance.

Figure 1. Western and central Washington. 1, Birch Bay No. 1 well; 2, Engstrom Community Well No. 1; 3, Alderwood No. 1; 4, Rattlesnake Hills gas field. Tri-Cities, Richland, Pasco, Kennewick.

Hydrous pyrolysis of Type II coals and adjacent shales penetrated in the Birch Bay No. 1 well, drilled by American Hunter and others, indicates that both shales and coals have potential to generate light hydrocarbons (Fig. 4). Figure 5 indicates that these rocks are rich in liptinitic coal macerals. Brown and Ruth (1984) noted the presence of exinitic material in several other Puget trough wells, but data from Cohen (1983) show that coals from eastern King and Pierce Counties do not contain Type II kerogen. These King and Pierce County coals fluoresce.

Geothermal gradients in the Puget trough average a remarkably low 23°C/km (Blackwell and others, 1985). The Birch Bay No. 1, drilled in the Bellingham sub-basin (central Puget trough), has a 14.4°C/km gradient, as determined from numerous drillstem test measurements. However, Puget trough geothermal gradients increase eastward abruptly across the foothills to the crest of the Cascade mountains, where gradients average 44°C/km and where anthracite is present. Vitrinite reflectance mapping (Walsh and Lingley, 1991) indicates that geothermal paleogradients conform closely to present-day gradients. In general, geothermal paleogradients in the central Puget trough were equal to or less than the present gradients. Best-fit linear regressions of Puget trough geothermal gradient indicators versus depth are unusually steep. Samples from many wells display little increase in vitrinite reflectance (R_o), thermal alteration indices (TAI), and T_{max} pyrolysis values as depth increases (Brown and Ruth, 1984; Summer and Verosub, 1987; Bustin, 1990; Walsh and Lingley, 1991). Consequently, the apparent oil-generative window commonly appears to be 3,000 m long but lies below the total depth of most Washington wildcats. Mature values of R_o, TAI, and T_{max} in outcrop samples do not necessarily condemn underlying prospects.

Petroleum seeps and shows are present in many parts of the state. Stripper thermogenic-gas production has been achieved at Ocean City (Palmer and Lingley, 1989); near Ferndale (McFarland, 1983; Hurst, this issue); and at Benton City (Hammer, 1934). The last produced a total of 1.3 billion ft^3 of methane from the Rattlesnake Hills field. Twelve-thousand barrels of paraffinic oil were produced at Ocean City. Oils from the Olympic Peninsula (Kvenvolden and others, 1989b; Palmer and Lingley, 1989) and condensates from the Columbia Basin are paraffinic and range from 37° to 52° API gravity. Saturate-fraction chromatography indicates that all of these oils are immature and have carbon preference indices mostly greater than 1.2. Although bona fide shows are rare in the center of the Puget trough and the Fuca-Tofino basin, few wells have been drilled into the oil-generative window (Walsh and Lingley, 1991). Apparent live-oil shows were logged in Tertiary sections in the Engstrom Community No. 1, the Alderwood No. 1, and the Phillips State No. 1. Gas seeps are present near Bellingham, Benton City, and Black Diamond. These have been ascribed to glacial, biogenic, or low-temperature coal alteration origins because of the great depths to thermogenic gas-generative zones in these areas. However, analyzed gases contain significant fractions of methane having delta-C^{13} heavier than -55, suggesting a thermal origin (Hurst, this issue; Kvenvolden and others, 1989a; this study).

Little information is available to link seeps and shows with corresponding source rocks. Kvenvolden and others (1989b) identified rare biomarkers in both Olympic coast oils and organic detritus from adjacent turbidites of the Olympic core complex. Oils from Ocean City have bulk chemistries and triterpane (m/z 191) distributions that are essentially

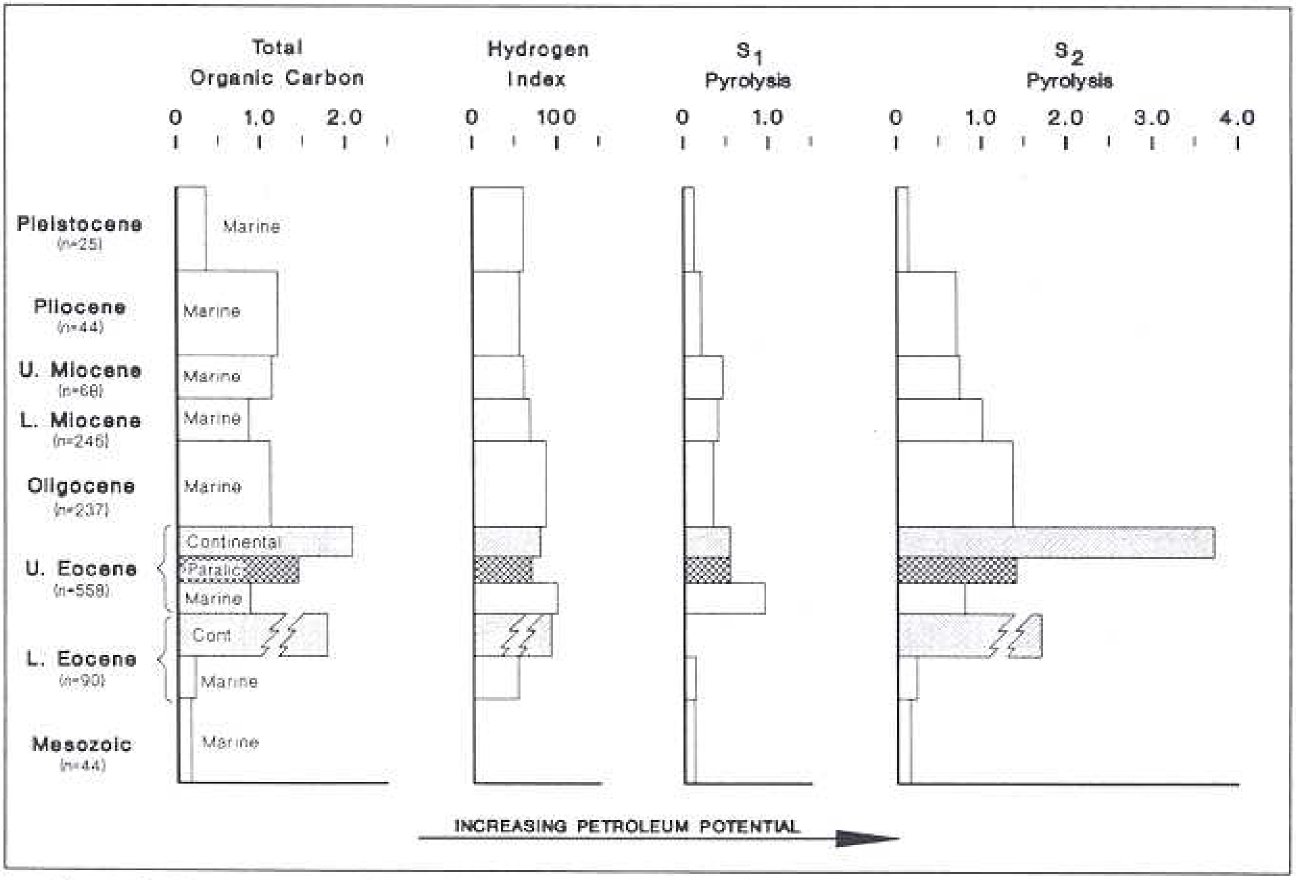

Figure 2. Some organic geochemical characteristics of selected sedimentary rocks in Washington. The dominant depositional environments for each time-stratigraphic interval are: marine, paralic, and continental. Data from coals are not shown except for lower Eocene rocks where broken bars indicate that the mean values are off-scale but not enriched relative to other time-stratigraphic intervals.

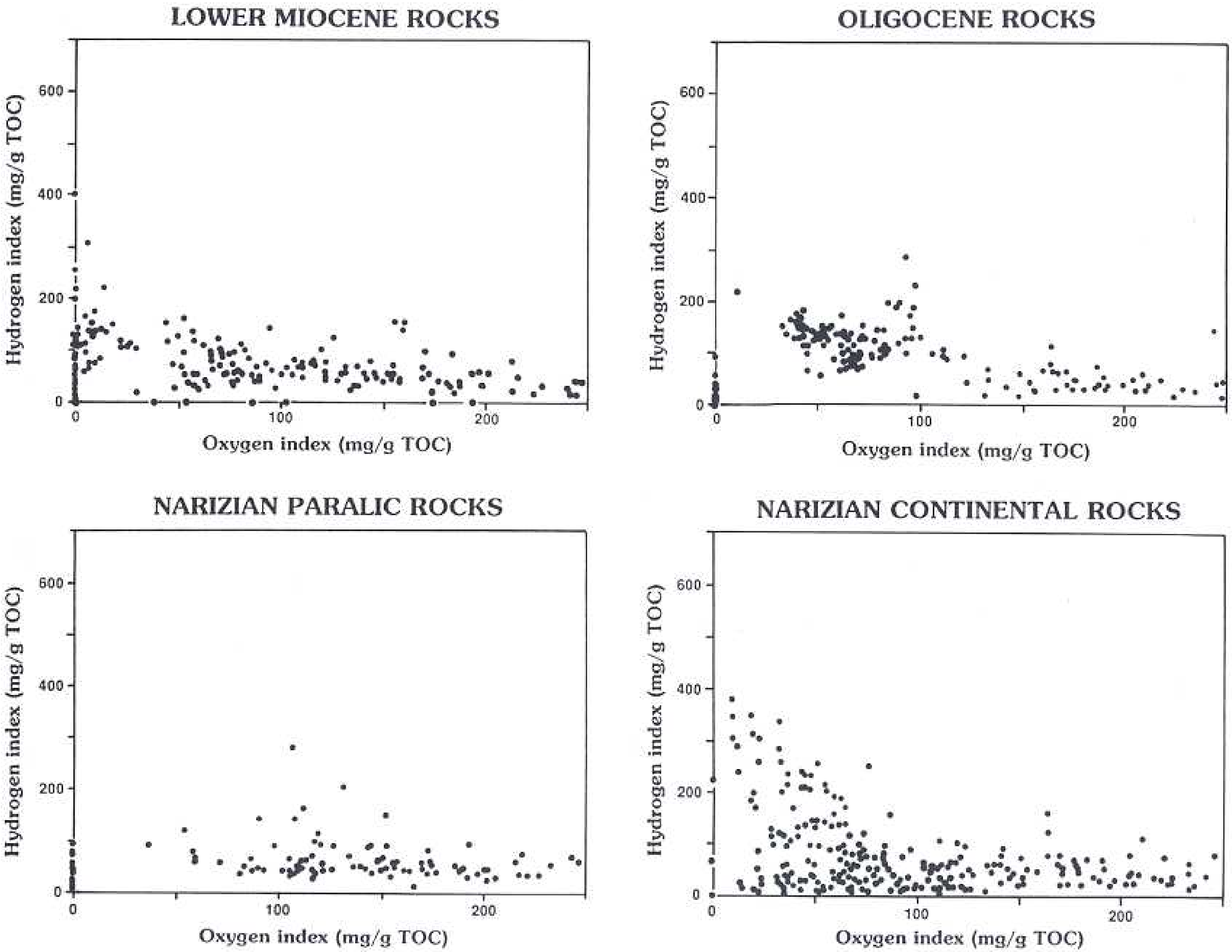

Figure 3. Pseudo van Krevelen diagrams for various stratigraphic intervals sampled in Washington wells and measured sections. All four diagrams indicate that gas-prone Type III kerogen predominates. However, Narizian-stage rocks deposited in continental environments show significant Type II (light-liquids- and gas-prone) kerogen, as well as hydrogen enrichment relative to coeval marginal-marine rocks and rocks in other stratigraphic intervals. Data sources are cited in text. TOC, total organic carbon.

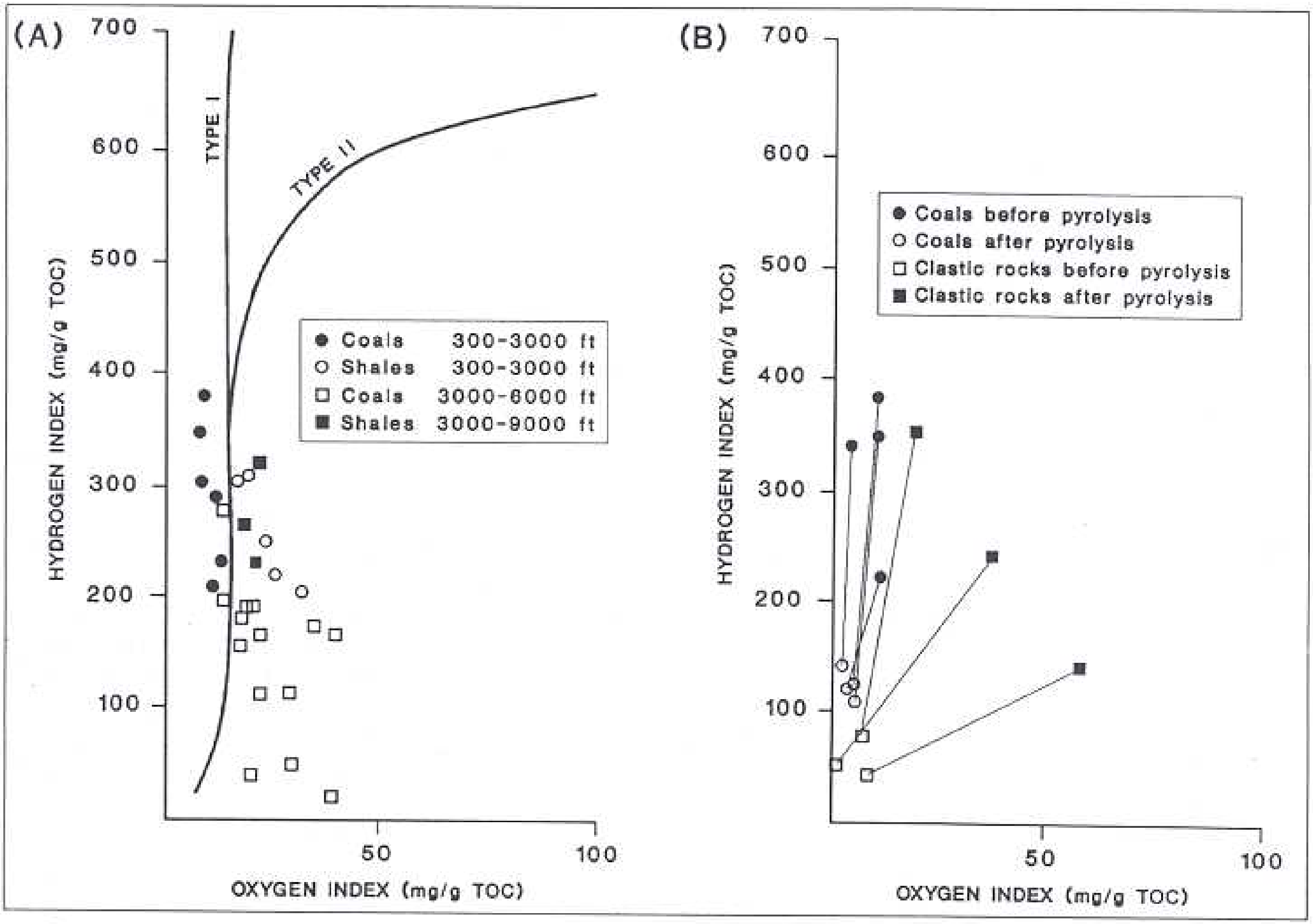

Figure 4. Pseudo van Krevelen diagrams for Birch Bay No. 1 samples. **A.** Results from Rock-Eval analysis. **B.** Results before and after hydrous pyrolysis. TOC, total organic carbon.

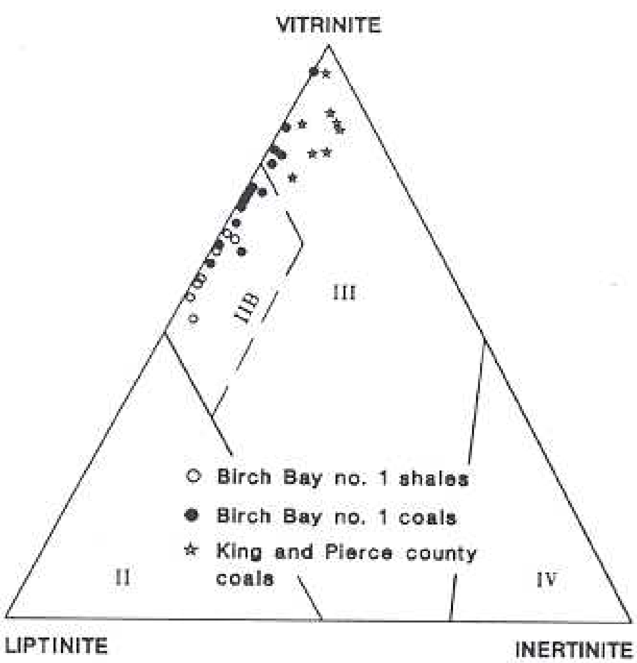

Figure 5. Maceral composition of some Washington coals (Cohen, 1984; this study). Kerogen types are indicated by roman numerals.

identical to those of oils tested from wells and seeps near Forks, which is located about 62 mi to the north. This suggests a cogenetic relation for coastal oils (Palmer and Lingley, 1989). C_{20} diterpane in Puget trough wells such as the Engstrom Community No. 1 and Alderwood No. 1 (Brown and Ruth, 1984) indicates a terrestrial source for minor shows logged in these wells.

From this body of data, we conclude that Washington has potential for gas, condensate, and light-oil accumulations. In order to explore for such pools, operators should map areas with potential to preserve Types II and III kerogen (reducing depositional environments) and be certain that peak-generative conditions will be present within the depths to be drilled.

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Geology and Preliminary Hydrocarbon Evaluation of the Tertiary Juan de Fuca Basin, Olympic Peninsula, Northwest Washington

Alan R. Niem
Dept. of Geosciences
Oregon State University
Corvallis, OR 97331

and

Parke D. Snavely, Jr.
Office of Marine Geology
U.S. Geological Survey
Menlo Park, CA 94025

The Juan de Fuca basin (JDFB) extends from near Striped Peak northwestward to Cape Flattery along the northern margin of the Olympic Mountains (Fig. 1). This Tertiary deep marginal basin continues north and northwest beneath the Strait of Juan de Fuca and the Pacific Ocean to the Canadian shelf and slope and is referred to as the Tofino basin (TB) by Shouldice (1971) and the Tofino–Fuca basin by Snavely and others (1980). The northern flank of the JDFB–TB is exposed in a narrow belt of shallow- and deep-marine Paleogene and early Neogene strata that crop out along the southern coast of Vancouver Island (Snavely and others, 1980; Cameron, 1971, 1979; Bream, 1987). The JDFB may have extended farther east at times (De Chant, 1989) and (or) may have been connected with other deep-marine basins that had different sediment source areas (Snavely and others, 1980).

The southern flank of the JDFB consists of more than 6,000 m of homoclinal north-dipping strata of middle Eocene to early Miocene age (Brown and others, 1960; Gower, 1960; Snavely, 1983; Snavely and others, 1986, 1989). Lithic arkosic to lithic turbidite sandstone, deep-marine mudstone, and subordinate polymict conglomerate and sedimentary breccias unconformably overlie lower Eocene oceanic